Force Sensorless Power Assist Control for Wheelchair on Flat Road Using Recursive Least Square with Multiple Forgetting

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Power Assist Wheelchair (PAW) has being developed for users and caregivers in current high aged society. As a human-machine system, it is important for PAW to sense the human force and operation. In this paper, a Disturbance Observer (DOB) based force estimator is applied to PAW to estimate external forces including the human force and the friction force. In conventional methods, the friction force is compensated using the Viscous and Coulomb friction model. However, the viscous coefficient and the coulomb coefficient need to be modeled beforehand. If the environment is changed, this two coefficients need to be modeled again. This makes the force sensorless control difficult to be realized. In this paper, a Recursive Least Square (RLS) with multiple forgetting method is used to estimate human force and the friction force simultaneously. Using the proposed method, it will not be necessary to model friction force beforehand. Furthermore, since the friction coefficient can also be estimated by using the proposed method, the assist rate can be adjusted in different environments. Simulation and experimental results demonstrate the validity of the proposed method.

Keywords: power assist wheelchair, disturbance observer, force sensorless, recursive least square, multiple forgetting, high aged society

1. Introduction

Mobility is one of the basic requirements of human. During the last 100 years, wheelchair was one of the important devices to assist handicapped people to regain some mobility. Basically, the wheelchairs can be divided into three main categories by considering the operating levels: Manual Wheelchair, Power Assist Wheelchair (PAW), Electric Wheelchair (EW). The wheelchair allows a user to move at long distance. However, propelling a manual wheelchair for a long time may cause pain in the users' arm (1). PAW is developed to reduce the risk of arm injury. Nowadays, the market demand for PAW has increased continuously since the users can drive the PAW with less physiologic and biomechanical effort.

Generally speaking, PAW has two independent driving wheels, in which two in-wheel motors are installed. There is a torque sensor in each handrim to detect the human torque respectively. Therefore the assist torque can be offered by each in-wheel motor using the information from the torque sensors.

PAW has the advantages of effort-saving and good mobility. Such system involves a full human-machine interaction which requires good performance in different conditions. Various kinds of technologies are developed. For instance, Oh *et al.* proposed an Integrated Motion Control (IMC) method to control the PAW in the longitudinal, lateral, and the pitch directions independently (2). K.Kim proposed Yaw Motion Control for PAW under lateral disturbance environments (3) (4), aiming at removing the influence from the lateral disturbance. Seki *et al.* proposed a safety driving control for PAW based on regenerative brake (5). When the velocity of the wheelchair increases on the slope, this control system will switch from " driving mode " to " braking mode ". Shibata and Murakami proposed Repulsive Compliance Control in pushing tasks (6), this makes users easy to carry out pushing task. Tashiro and Murakami proposed a step passage control for PAW to passing over steps (7). In (6) and (7), a disturbance observer (DOB) based force estimator (8) is used to detect human force instead of torque sensors.

Using DOB based estimator to replace torque sensors has many advantages. Firstly, it can reduce the cost and weight of the entire system since the torque sensors are almost the most expensive and largest sensor in the PAW. Secondly, In highly aged societies, the assist device should be designed both useful and convenient for users and caregivers. Force sensors can only detect force when it is applied on the sensors. For the caregiver type, four torque sensors are needed on the wheelchair which makes the entire system expensive and heavy. A DOB based estimator can solve this problem. DOB estimates external force including human and friction force. Therefore, it is important to separate human force from the external force to guarantee the good performance of the entire system.

In conventional methods, the Viscous and Coulomb friction model is used to compensate the friction force. It means that the viscous coefficient and the coulomb coefficient need to be modeled beforehand. When the environment is changed, the coefficients need to be modeled again. This makes the conventional method complicated and incon-

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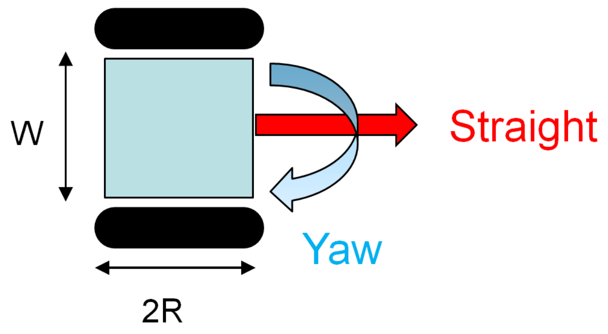

Fig. 1. The basic structure of a wheelchair

venient.

The friction force can be described by the Viscous and Coulomb friction model. Since the wheelchair is always moving in a low speed, the viscous coefficient can be regarded as zero (9). That means the friction force can be regarded as a constant value if the environment does not change. In this paper, a Recursive Least Square (RLS) with multiple forgetting method (12) is used to separate human force and the friction coefficient simultaneously. Using this method, the human force can be estimated without compensating the friction force and the assist gain can be adjusted according to the estimated friction coefficient.

This paper is organized as follows. A model of a wheelchair by considering the longitudinal and the lateral directions will first be discussed in Section two. A DOB based force estimator is introduced in Section Three. The multiple forgetting RLS based method (12) to estimate human force and friction coefficient will be discussed in Section Four. The overall control system will be introduced in Section Five. The experimental setup and conditions will be introduced in Section Six. The experimental results are shown in Section Seven. Finally, the conclusion and the future work will be discussed.

2. Dynamic Modeling of a Wheelchair by Considering the Longitudinal and the Lateral Directions

A power assist wheelchair is driven by two independent electric in-wheel motors. Figure 1 shows a schematic of a wheelchair. In this paper, three assumptions are made:

- The weight of the person and the wheelchair is symmetrical.
- Slip between the road and the wheels can be neglected.
- The wheelchair will not move in the pitch direction which means the casters will not leave the road.

Most wheelchairs are designed in a symmetrical way and the weight of the person are considered to be symmetrical too. Since the wheelchair is always move in a low speed, the slips between tire and road can also be neglected. An assist limitation will also be set to prevent over turning.

There are two basic motions for wheelchairs, the straight motion and the rotational motion. Here ω_S means the angular velocity of the straight motion, ω_Y means the angular velocity of the rotational (yaw) motion, and ω_R and ω_L represent the angular velocity of the right and the left wheel, respectively. ω_S and the ω_Y can be written as

$$\omega_S = (\omega_R + \omega_L)/2, \cdots\cdots (1)$$

$$\omega_Y = (\omega_R - \omega_L)/2. \cdots\cdots (2)$$

The equation 1 and 2 can be used not only for the velocity but also the angular information, input torque, the motor torque, and the disturbance from each side. A matrix can be used here to explain the transformation.

$$\begin{bmatrix} \omega_S \\ \omega_Y \end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 \\ 1/2 & -1/2 \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} . \cdots\cdots (3)$$

The linear velocity of the straight motion and the yaw rotation speed can be written as :

$$v_S = R\omega_S , \gamma = \frac{2R}{W}\omega_Y . \cdots\cdots (4)$$

R and W are the radius of the driven wheel and the width of the wheelchair, respectively, as shown in Figure 1. The motion of wheelchair (+human) can be divided into four parts−−the entire straight motion, the entire rotational motion, the left wheel motion, the right wheel motion. These four motions can be written as below:

$$M_{v_s}\dot{v}_s + D_{vs}v = F_L + F_R + d_{v_s}, \cdots\cdots (5)$$

$$J_\gamma\dot{\gamma} + B_\gamma\gamma = \frac{W}{2}(-F_L + F_R) + d_\gamma, \cdots\cdots (6)$$

$$J_w\dot{\omega}_R + B_w\omega_R = \tau_R - f_R + d_{wR}, \cdots\cdots (7)$$

$$J_w\dot{\omega}_L + B_w\omega_L = \tau_L - f_L + d_{wL}. \cdots\cdots (8)$$

Here, M_v and D_v represent the total mass and damping coefficient, respectively. F_R,F_L and d_{v_s},d_γ are the driving force of each side and disturbance of the straight and yaw motion. f_L and f_R represent the friction force of each side. τ_L and τ_R means input torque, d_{wR} and d_{wL} are the disturbance except friction force of each side. J_γ and J_ω stand for the inertia of the yaw motion and the wheel. The B_γ and B_ω are viscous coefficients of yaw motion and wheel, respectively. Based on the equation 1, 2, 5 to 8, we can get a dynamic function relate only to the two rear wheels.

$$J_S\dot{\omega}_S + B_S\omega_S = \tau_S + d_S, \cdots\cdots (9)$$

$$J_Y\dot{\omega}_Y + B_Y\omega_Y = \tau_Y + d_Y. \cdots\cdots (10)$$

Where

$$J_S = J_\omega + \frac{1}{2}M_vR^2, \cdots\cdots (11)$$

$$J_Y = J_\omega + \frac{1}{2}J_\gamma(\frac{2R}{W})^2, \cdots\cdots (12)$$

$$B_S = B_\omega + \frac{1}{2}D_vR^2, \cdots\cdots (13)$$

$$B_Y = B_\omega + \frac{1}{2}B_\gamma(\frac{2R}{W})^2 \cdots\cdots (14)$$

$$\tau_S = \frac{\tau_R + \tau_L}{2} \cdots\cdots (15)$$

$$\tau_Y = \frac{\tau_R - \tau_L}{2}. \cdots\cdots (16)$$

Here, J_S and J_Y represent the inertia of straight and the rotational motion, respectively. B_S and B_Y represent the viscous of each motion. τ_S and τ_Y stand for the straight and yaw torque, respectively. d_S and d_Y are the disturbance of the straight and yaw motion. It can be seen from the equation 9 and 10 that the straight and rotational potions are proportional to the common component and the differential component.

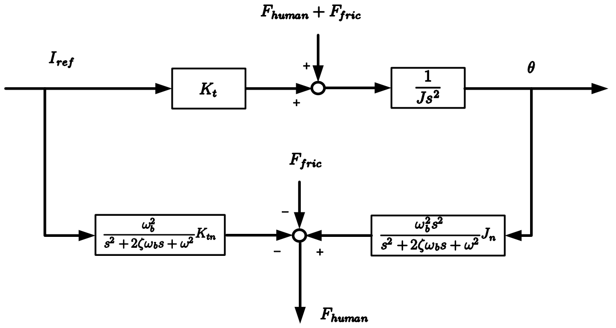

Fig. 2. The low-acceleration estimator based torque observer

3. Human Force Detection

In this section, a DOB based force estimator is applied to detect external force. The human force can be estimated separating from the external force.

3.1 Low acceleration estimator based disturbance observer The external force can be detected by a DOB based force estimator. However, the friction force are also included in the external force. As a human-machine system, it is important for PAW to sense the human force, and the assist torque should be just applied to human torque. That means it is important to separate human force from the entire external force.

A low acceleration estimator based force disturbance observe shown in Figure 2 is used to detect human force. It is obviously that wheelchairs often move in a low speed and low acceleration which makes it more difficult to get high-accurate acceleration information from the encoders. To get high accurate acceleration, it is common to use a high resolution encoder. However, to use a high resolution encoder may make the entire system expensive. If the low-resolution encoders can be used in the application, the cost can be cut down. The low-acceleration estimator (LAE)(11) developed by Lee *et al.* is employed to provide the required acceleration and velocity. The external force F_{ext} can be estimated as

$$F_{ext} = \frac{\omega_b^2(s^2 J_n\theta - I_{ref}K_{tn})}{s^2 + 2\zeta\omega_b s + \omega_b^2}\frac{1}{R} \cdots\cdots\cdots\cdots\cdots\cdots \quad (17)$$

In experiments, ω_b is set as 10 rad/s to take balance between the tracking capability and the estimator performance. ζ is set as 0.707 to provide the fast response without overshot.

3.2 Separating human force and friction force The external force can be obtained by using a DOB based force estimator which includes human force and friction force. In conventional methods, the friction force should be compensated using a friction model such as the Viscous and Coulomb friction model. It is inconvenient since the viscous and the coulomb need to be identified beforehand. Noticing that the friction force can be regarded as a constant value(9), we can simplify this problem as below

$$F_{ext} = F_{human} - \mu Mg \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (18)$$

Where F_{ext} means the external force including human force and friction force. F_{human} is the human force. μ is the friction coefficient, M is the mass of the overall system, and g is the gravitational acceleration. F_{human} is time varying and the parameter μ is a constant value. If we differentiate the equation 18, the constant part (friction part) will be disappeared. However, by using this method to calculate human force, the error will be added up since it needs to integrate the differential part. In this paper, the Multiple forgetting Recursive Least Square method is used here to estimate the human force and the friction coefficient.

4. Multiple forgetting RLS method

4.1 The multiple forgetting RLS algorithm In (12), a multiple forgetting RLS method is proposed to estimate two parameters when one parameter is constant and another is time-varying. In this application, this method is used to estimate human force and friction coefficient simultaneously. We can conclude this problem in the following structure:

$$F_{ext} = F_{human} - \mu Mg, \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (19)$$

$$y = \phi^T\theta, \phi = [\phi_1, \phi_2]^T, \cdots\cdots\cdots\cdots\cdots\cdots \quad (20)$$

$$\theta = [\theta_1, \theta_2]^T = [F_{human}, \mu]^T, \cdots\cdots\cdots\cdots\cdots \quad (21)$$

$$y = F_{ext}, \phi = [\phi_1, \phi_2] = [1, -Mg]. \cdots\cdots\cdots\cdots \quad (22)$$

The algorithm can be written as follow:

$$\hat{\theta}(k) = \hat{\theta}(k-1) + K(k)(y(k) - \phi^T(k)\hat{\theta}(k-1)) \cdots\cdots \quad (23)$$

$$K(k) = \frac{1}{1+\frac{P_1(k-1)\phi_1(k-1)^2}{\lambda_1}+\frac{P_2(k-1)\phi_2(k-1)^2}{\lambda_2}}\begin{bmatrix} \frac{P_1(k-1)\phi_1(k)}{\lambda_1} \\ \frac{P_2(k-1)\phi_2(k)}{\lambda_2} \end{bmatrix} \quad (24)$$

$$K_1(k) = P_1(k-1)\phi_1(k)(\lambda_1 + \phi_1^T(k)P_1(k-1)\phi_1(k))^{-1} \quad (25)$$

$$P_1(k) = (I - K_1(k)\phi_1^T)P_1(k-1)\frac{1}{\lambda_1} \cdots\cdots\cdots\cdots\cdots\cdots \quad (26)$$

$$K_2(k) = P_2(k-1)\phi_2(k)(\lambda_2 + \phi_2^T(k)P_2(k-1)\phi_2(k))^{-1} \quad (27)$$

$$P_2(k) = (I - K_2(k)\phi_2^T)P_2(k-1)\frac{1}{\lambda_2} \cdots\cdots\cdots\cdots\cdots\cdots \quad (28)$$

4.2 The simulation results to separate human torque The simulation results are shown in Figure 3 ,4 and 5. In this simulation, human force is expressed in a sine function, and the friction coefficient is set as 0.012. The mass of the entire system is set as 100 *kg*. g is set as 9.8 m/s^2. The external force obtained from DOB is expressed in figure 3, the friction force is assumed to be a constant value. We assume that the environment will not change, so the forgetting factor λ_2 represents the changing rate of the friction coefficient will be set as 1. The forgetting λ_1 for human force is set as 0.95 according to the force characteristic. According to the simulation results, it is clear that by using this method, the human force can be correctly separated from the external force without friction compensation beforehand.

4.3 Discussion about RLS with multiple forgetting The normal type of RLS with single forgetting factor can be written as

$$\hat{\theta}(k) = \hat{\theta}(k-1) + K^{'}(k)(y(k) - \phi^T(k)\hat{\theta}(k-1)) \cdots \quad (29)$$

$$K^{'}(k) = P(k-1)\phi(k)(\lambda + \phi^T(k)P(k-1)\phi(k))^{-1} \cdots \quad (30)$$

$$P(k) = (I - K^{'}(k)\phi^T(k))P(k-1)\frac{1}{\lambda} \cdots\cdots\cdots\cdots \quad (31)$$

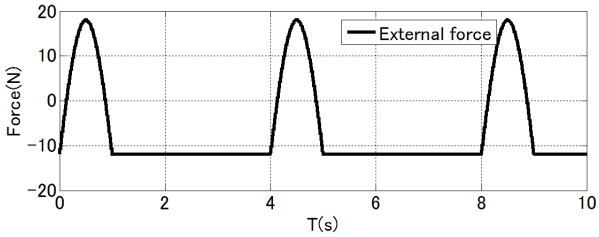

Fig. 3. External force from DOB

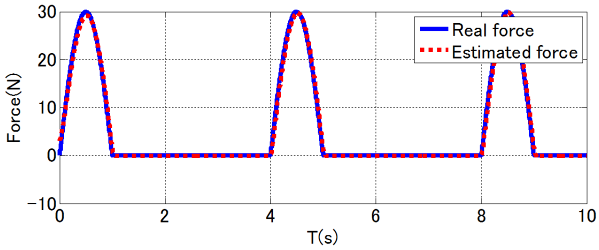

Fig. 4. Human force

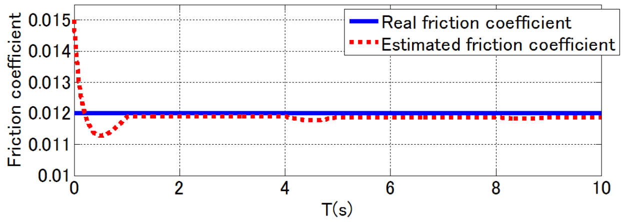

Fig. 5. Friction coefficient

Equation 23 is similar to the standard update form of the well known RLS estimation with single forgetting factor (Equation 29). However, the gains of the standard and the proposed form are different. The covariance of RLS with Multiple forgetting is diagonal, while the normal one has a crossterm of $P_{12}(k-1)$ and $P_{21}(k-1)$. Therefore, the method proposed by (12) can reduce the caculation.

There are some reasons why this method can be used in this application to separate human force and friction force. Parameters are updated with different forgetting factors, and this method can decouple the updating step of the covariance of different parameters. In this application, the friction force is assumed to be constant, and the human force is assumed to be change much faster than the friction force. So the forgetting factors can be adjusted to meet the different changing rates.

Moreover, there is another algorithm about RLS with multiple forgetting (13). This algorithm is very similar to the algorithm proposed in (12), however, the covariance of this RLS method also has a crossterm of $P_{12}(k-1)$ and $P_{21}(k-1)$, and it is weak toward noise. In this application, the algorithms proposed by (12) and (13) are both alright, because there is a low pass filter in the DOB and the DOB based force estimator part, the effect from the noise will not have a large effect toward the overall system.

5. The Overall Control System

Figure 6 shows the entire control system. Subscripts $human$, $fric$, n and ref stand for input from the human, input from friction force, nominal value and reference, respectively.

The control system can be divided into four parts. The first part is a DOB and a DOB based force estimator. A DOB is constructed here for the system to track for the reference. The robustness of the whole system is improved by using the DOB. The DOB based force estimator is used in the system to estimate external force including human force and friction force. The second part aims to separate human force and the disturbance to ensure the assist force will only be applied to the human force. The third part is the power assist part, the power assist gain can be designed according to the estimated friction force coefficient, if the friction force coefficient is high, the assist gain can also be set high to support the user. If the environment changes, the friction force can be estimated again by resetting the program. Finally, the velocity reference will be tracked in the feedback loop.

6. Experiments

6.1 Experimental setup The experimental set up is shown in Figure 7. The wheelchair used here is JW-II which is produced by YAMAHA. Force sensors are set in hand-rims so the users can move the wheelchair by propelling the hand-rims. It should be noticed that the measured data from force sensors here is only used to evaluate the proposed method for human force estimation. And the force sensors will not be used in the control system. The velocity information can be obtained from the encoders. More information is shown in Table 1. The parameters used in the experiments are shown in Table 2. The viscous coefficient and the coulomb coefficient will only be used in the proposed method.

Table 1. Variables of equipments

Parts	Type
PAW	JW-II
DSP	s-BOX
Encoder	RE20F-100-200

Table 2. Parameters

Mass of the wheelchair and human	M	105 kg
Forgetting factor for human force	λ_1	0.95
Forgetting factor for friction coefficient	λ_2	1
Radius of the wheel	R	0.33 m
Inertia of the straight motion	J_s	5.73 kgm^2
Inertia of the yaw motion	J_Y	7.19 kgm^2
Viscous coefficient	B	0.21 $Nm/(rad/s)$
Coulomb coefficient	D	4.2 Nm

6.2 Experiment 1: Going straight Figure 8 shows the experimental environment of Experiment 1. The users will move the wheelchair going straight forward and then going straight backward. The purpose of this experiment is to verify the effectiveness of the proposed human force estimation method when going straight.

6.3 Experiment 2: Going straight with sinusoidal turning Figure 9 shows experimental environment of Experiment 2. The wheelchair will move with sinusoidal turning. We want to verify the effectiveness of the proposed method when wheelchair is turning.

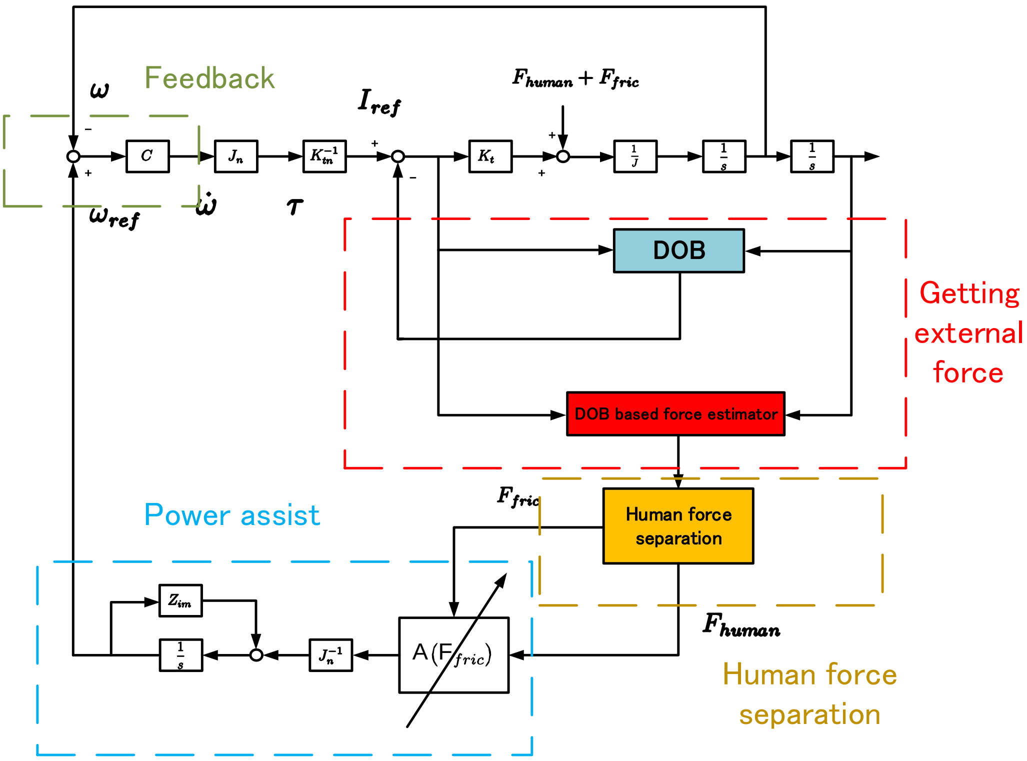

Fig. 6. The entire control system

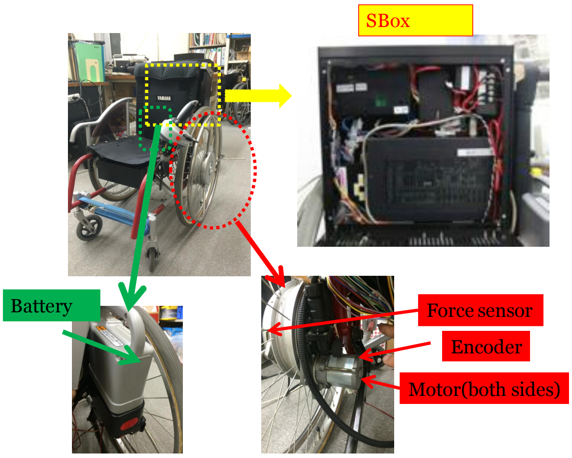

Fig. 7. Experimental setup

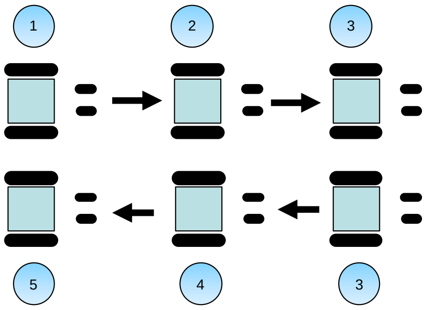

Fig. 8. Experiment 1

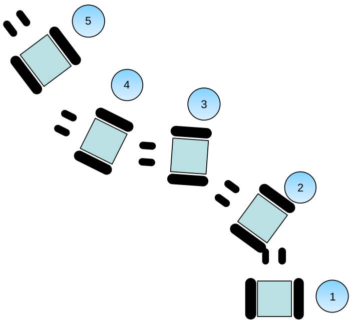

Fig. 9. Experiment 2

7. Experimental Results

7.1 Experiment 1: Going straight Experimental results of going straight are shown in Figure 10. The blue line is the real human torque which is detected by the torque sensor. The green dashed line stands for the estimated human force with conventional method compensating the friction force by using the Viscous and Coulomb friction model. The red dot line represents the estimated human force by the proposed method using RLS with multiple forgetting.

The user will drive the wheelchair move forward until 12.5 seconds. From 12.5 seconds, the user started to move the wheelchair backward. The proposed method show good performance even there is no friction force compensation beforehand.

7.2 Experiment 2: Going straight with sinusoidal turning Experimental results of going straight with sinu-

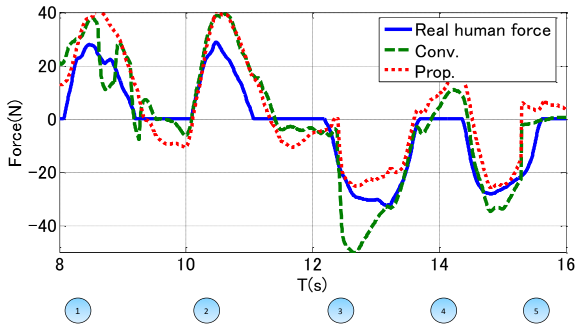

Fig. 10. Experiment 1: Going straight

soidal turning are shown in Figure 11. Figure 11 shows the force information when going straight with sinusoidal turning. The color code of each line is same as that of Figure 10.

In this experiment, as shown in Figure 9. The wheelchair will go straight with sinusoidal turning. The user is changing the direction between 7.5 to 9 seconds, and 13 to 15 seconds, the human force can not be estimated as well as the Experimental 1. That is because when the direction of wheelchair is changing, there will be some other disturbance from the casters or axle (9) (10). But in general, the proposed method performs well.

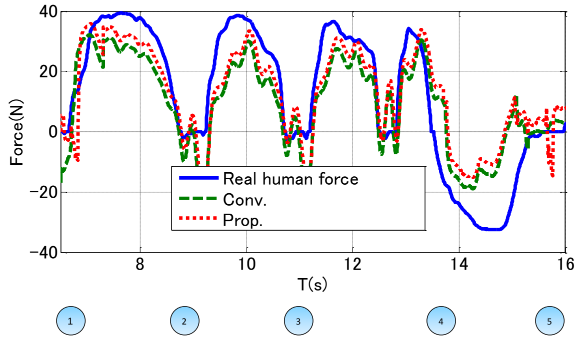

Fig. 11. Experiment 2: Going straight with sinusoidal turning

8. Discussion and the Future Work

8.1 About the dynamic modeling for PAW A model considering the longitude and the lateral directions is used in this paper. Based on the fact that users feel different when the wheelchair is going straight and rotation. Different assist method can be designed according to the straight motion and the yaw motion. Using this model, the straight motion and the yaw motion of the wheelchair can be controlled separately which makes the overall system more human-friendly.

8.2 About the experimental results Using RLS with multiple forgetting, no friction force compensation will be needed beforehand and the estimated results turn out to be good. The proposed method can also be applied to various environments with only resetting the program.

8.3 About RLS with multiple forgetting Different forgetting factors can be set for each parameter. In this application, the friction coefficient is assumed to be constant, and the human force is assumed to change much faster. The forgetting factor for human force are set according to the human force characteristics. Note that this method is applied for the PAW for the user type, the human input change much faster than the friction force. For the caregiver type, more discussion is needed.

8.4 About the future work In this paper, a method using RLS with multiple forgetting to separate human force and friction force is proposed in this paper. By using the proposed method, the human force can be estimated without compensating the friction force. However this method can not be used to separate the changing disturbance, which means this method can not be used in the slope environments. In future, some new method should be developed to separate human force and disturbance in slope environments.

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